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Effect of post annealing on electrical properties of (Ni/Au)/$Al_{0.20}Ga_{0.80}N$ Schottky contacts

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Abstract

The effects of thermal annealing on the electrical properties of Ni/Au Schottky contacts on n-type $Al_xGa_{1-x}N$ (x=0.20) were investigated by current-voltage (I-V) and capacitance-voltage (C-V) measurements. The Schottky barrier height (SBH) of as-deposited contacts was found to be 0.946±0.033 eV (from I-V) and 1.120±0.047 eV (from C-V) with an ideality factor of 1.655±0.137. The values of SBH obtained from the C-V measurements were found to be higher than that of obtained from the I-V measurements. This was attributed to the presence of the lateral inhomogeneities of the barrier height. The values of SBH slightly increased after the annealing temperatures at 300, 400 and 500ºC. The highest value of SBH for Ni/Au Schottky contact was obtained after annealing at 600ºC and the value was 1.521±0.032 eV. The good performance of the annealed Ni/Au contact can be attributed to reaction of Ni with the GaN cap layer of AlGaN substrate, and formation of intermetallic compounds such as GaNi and reduced interfacial defects at the metal/GaN interface.

Keywords: Schottky barrier height, AlGaN, Electrical properties, Barrier inhomogeneity, Thermal annealing

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1. Introduction

III-nitride semiconductor materials and its ternary alloys especially aluminum gallium nitride (AlGaN), have been widely investigated for fabrication of high power electronics and optoelectronics devices due to the properties of direct wide-band gap, high electron saturation velocity and large breakdown field. In the last few years many commercial company successfully produced GaN or AlGaN based devices such as transistors and pin diodes. Owing to their wide direct band-gap, superior radiation hardness and high temperature resistance, nitride-based devices are potentially useful in many commercial and military applications. Although these developments, still structural properties and device behaviors against the exterior effects such as temperature or annealing have to be investigated.

It is known that, dislocation density in GaN and/or AlGaN epitaxial layers was high due to the large differences in lattice constant and thermal expansion coefficient between GaN and sapphire. Also nitrogen deficiency causes large amount of point defects even in metal organic chemical vapor deposition (MOCVD) growth. These defects determine the conduction type, doping density and total amount of leakage current conduction mechanisms etc. Therefore, reducing the leakage current and controlling substrate properties are important issues for GaN-based devices. Also improvement of the parameters such as barrier height (BH) and ideality factor are important to fabricate a proper device. Most preferred methods to improve the Schottky barrier diode (SBD) parameters are thermal annealing and surface treatment. Many studies report improvement on the Ni/Au-based GaN or AlGaN devices parameters via different methods such as pre-chemical treatments [1-6], different etching treatments [7-11], interlayer passivation [12-17] and post annealing [18-24]. Reddy et al. [2] investigated the effect of tetra methyl ammonium hydroxide (TMAH) treatment on the electrical properties of Ni/Au/GaN SBDs. They showed that main electrical parameters such as n, BH, R_S, V_{bi}, I_0 and N_{SS} strongly depend on the TMAH treatment and electrical characteristics were also greatly improved by the TMAH treatment. Motayed et al. [10] studied on the two step treatment technique. They showed that the reactive ion etching and then wet etching in a boiling KOH solution for 5 min. produces the optimal electrical characteristics. Also they suggested that the treatments appear to suppress the electrical activity of the dislocations in the diodes. This etching process demonstrates a significant improvement in the reverse leakage current density $3x10^{-3}$ A/cm^2 at 18 V; it also produces an ideality factor as low as 1.14, a reverse breakdown voltage over 44 V, and excellent forward conduction characteristics. Arulkumaran et al. [14] fabricated AlGaN/GaN high-electron-mobility transistors ,(HEMTs)using a different passivation layers. They have demonstrated the surface passivation effects on the performance of AlGaN/GaN HEMTs using plasma enhanced CVD grown SiO_2, Si_3N_4 , and SiO_xN_y and increase of I_{Dmax} and g_{mmax} has been observed on the passivated SiO_2, Si_3N_4 and SiO_xN_y HEMTs when compared with the unpassivated HEMTs.

In our previous work [18], we have fabricated the Ni/Au contacts on n-GaN and we have investigated the thermal annealing effects on the electrical and structural properties of the Ni/Au contacts on-GaN. Annealing treatment was performed at a temperature ranging from 100 to 800°C in increments of 100°C for 2 min in argon ambient. The thermal stability of the Ni/Au Schottky contacts was evaluated by considering the change of the SBH with the annealing temperature. The variations in the chemical composition of the contacts with the annealing temperature were examined by XPS depth profile analysis. We found that the value of SBH of the as-deposited (Ni/Au)/GaN SBDs was found to be 0.560 ± 0.004 eV (obtained from I–V) and 0.622 ± 0.018 eV (obtained from C–V). The values of the SBH obtained from the C–V measurements were found to be higher than that of obtained from the I–V measurements. Furthermore, it is shown that the value of SBH increases with increasing annealing temperature. After the annealing at 700°C, the value of the SBH of Ni/Au Schottky contact was found to be 0.911 ± 0.010 eV (from I–V) and 1.765 ± 0.055 eV (from C–V). The obtained results are shown that the optimum annealing temperature for the Ni/Au Schottky contact is 700°C. The variation of Schottky barrier heights and ideality factors with annealing temperatures was attributed to the interfacial reactions of Ni/Au with GaN layer. The analysis of XPS depth profile showed that the formation of the gallide phases at metal/GaN interface upon annealing temperature could be the reason for the increase in the barrier heights of Ni/Au Schottky contact. Increment in barrier height by as much as 62.5 % was successfully recorded by thermal annealing at 700°C.

In this work we focused on thermal annealing effects on (Ni/Au)/$Al_{0.20}Ga_{0.80}N$ SBDs. Annealing treatment was performed at a temperature ranging from 100 to 700°C in increments of 100°C for 3 min in high purity argon ambient. The thermal stability of the Ni/Au Schottky contacts was evaluated by considering the change of the SBH with the annealing temperature.

2. Experimental procedure

In this study, unintentionally doped (uid) n-type $Al_{0.20}Ga_{0.80}N$ epitaxial layers grown by MOCVD on a 4H-SiC substrate were used. The epistructure of the wafer consists of 2 nm thin layer of GaN cap layer for protection purposes, $Al_{0.20}Ga_{0.80}N$ layer with a thickness of 21 nm, AlN layer with a thickness of 3 nm, Fe doped GaN buffer layer with a thickness of 1.8 µm and a 4H-SiC high-purity semi-insulating substrate with a resistivity of 10^5 Ωcm. The AlGaN substrates were cleaned consecutively acetone, methanol, trichloroethylene, deionized water (18 MΩ) 5 min. using ultrasonic agitation in each step. The substrates were then dried with high-purity nitrogen. After cleaning organic residues, the substrates were dipped in aqua regia (3:1 HCl:HNO_3) to remove the native oxide from the front surface of the substrate and boiling KOH (1M) to reduce the surface roughness, respectively. The Ti/Al (25 nm/105 nm) Ohmic metallization was deposited using magnetron DC sputtering for Ti and thermal evaporation for Al and a standard lift-off process was used to pattern the contacts. The contacts were annealed at 850°C for 1 min. in flowing high purity (6N) argon gas in a quartz tube furnace. The Ni/Au (30 nm/50 nm) Schottky metallization was then deposited using magnetron DC sputtering for Ni and thermal evaporation for Au and a standard lift-off process was used to pattern to form Schottky contacts with a diameter of 0.4 mm.

The I-V and C-V measurements of the (Ni/Au)/ $Al_{0.20}Ga_{0.80}N$ SBDs were accomplished by employing a computer-controlled HP 4140B picoamperemeter and Agilent E4980A LCR meter (20Hz-2MHz), room temperature in dark. Annealing was performed in the quartz tube furnace with flow (~10 ccm/s) of high purity Ar gas ambient. Annealing time was 3 minutes.

3. Results and discussion

3.1. I-V Measurement results

Fig. 1 shows the forward and reverse I–V characteristics of the as-deposited and annealed (Ni/Au)/$Al_{0.20}Ga_{0.80}N$ SBDs. For the as-deposited Ni/Au Schottky contact, the leakage current at 2 V is 4.0×10^{-7} A. It can be seen from Fig.

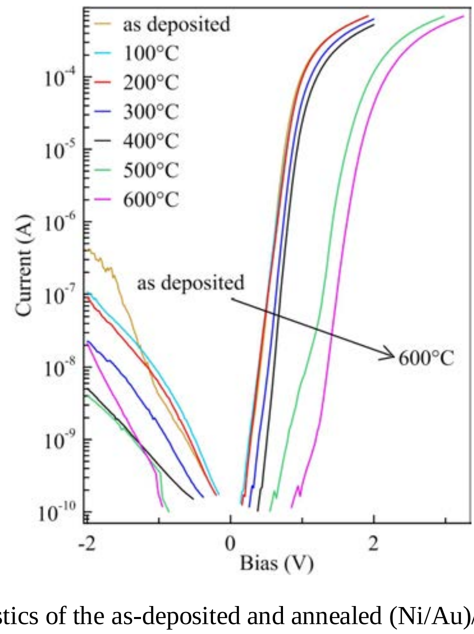

Fig 1. The I–V characteristics of the as-deposited and annealed (Ni/Au)/$Al_{0.20}Ga_{0.80}N$ SBDs.

1 that the thermal annealing effect was small below the annealing temperature of 400°C. However, the annealing effect on the leakage current reduction was revealed to be more significant at the annealing temperature of 500°C. The reverse leakage current was drastically reduced to the order of 10^{-9} A. Therefore, the annealing temperature of 500°C is crucial for the studied Ni/Au Schottky contacts.

The experimental I–V curves were analyzed using the thermionic emission theory (TET). The diode diameter was 0.4 mm and the effective Richardson constant was 32.702 $AK^{-2}cm^{-2}$ for n-type $Al_{0.20}Ga_{0.80}N$. The experimental values of the BH and the n after each annealing step were calculated from the intercepts and slopes of the straight-line portions of the semilog-forward bias I–V characteristics. The values of n and BH obtained depending on the annealing temperature for the diodes are given in Table 1.

Table 1. Characteristics diode parameters of the (Ni/Au)/$Al_{0.20}Ga_{0.80}N$ SBDs obtained from corresponding I-V graphics before and after thermal annealing steps. Each value represents the average of ten diodes.

Annealing temperature(°C)	n	Φ_b (eV)	Cheung's Function			
			n	R_S(Ω)	Φ_b (eV)	R_S (Ω)
as-deposited	1.655±0.137	0.946±0.033	2.133±0.431	1394.0±600.0	0.880±0.071	1394.0±598.8
100	1.914±0.325	0.902±0.020	2.235±0.198	877.3±200.9	0.862±0.048	879.0±201.0
200	2.014±0.269	0.906±0.025	2.232±0.394	1009.2±295.1	0.880±0.052	1009.7±292.4
300	1.608±0.156	1.056±0.019	2.042±0.312	1415.5±730.2	0.962±0.041	1415.8±725.4
400	1.407±0.071	1.145±0.037	2.210±0.322	1247.9±508.4	0.940±0.048	1250.2±506.0
500	1.497±0.232	1.213±0.068	2.723±0.812	1133.9±110.7	0.941±0.067	1140.4±109.5
600	1.755±0.077	1.521±0.032	4.003±0.385	1262.7±61.3	1.008±0.053	1265.7±61.6

According to the Table 1, the determined BH of the as-deposited Ni/Au Schottky contact was 0.946±0.033 eV. The SBH is lower than the theoretical value. This can be explained by the existence of the interfacial layer, structural defects such as the stacking faults, and dislocations on the AlGaN substrates.

The variation of barrier height of the Ni/Au Schottky contacts as a function of annealing temperature is shown in Fig. 2.

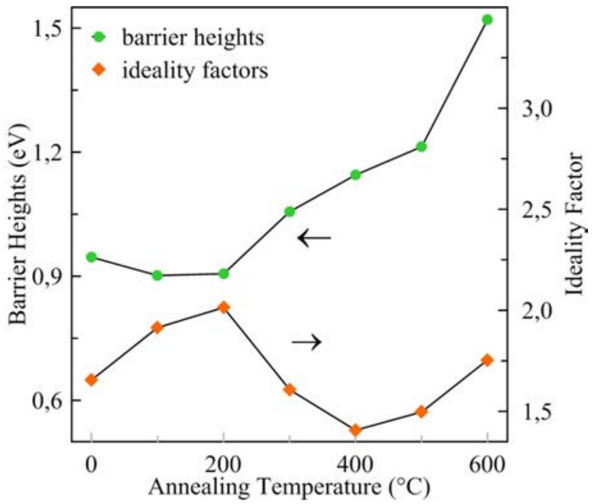

Fig. 2. The variation of barrier height of the (Ni/Au)/$Al_{0.20}Ga_{0.80}N$ SBDs as a function of annealing temperature.

The above observations reveal that first the value of the ideality factor slowly increases by annealing temperature up to 300°C and then decreases at the 400°C and re-increase above annealing temperatures of 500°C. This situation encountered may be due to the change of the interface state distribution and/or chemical composition formed between the metal and the semiconductor at the interface.

3.2. C-V Measurement Results

The reverse bias C–V characteristics of the as-deposited and annealed (Ni/Au)/$Al_{0.2}0Ga_{0.80}N$ SBDs were measured at room temperature. The values of SBH can also be determined from capacitance-current measurements. The plot of 1/C2 versus V should be a straight line with a slope of $2/q\varepsilon_s N_d$ and an intercept V_0 on the voltage, V_0 is related to the built in potential V_{bi} by the equation $V_{bi}=V_0 + kT/q$. Thus the barrier height is given by $\Phi_b^{(C\text{-}V)} = V_{bi} + V_n$, where V_n is the potential difference between the Fermi level and the bottom of the conduction band in the neutral region of semiconductor. The values of $\Phi_b^{(C\text{-}V)}$ and N_d for the (Ni/Au)/$Al_{0.20}Ga_{0.80}N$ SBDs are given in Table 2.

Table 2. Characteristics diode parameters of the (Ni/Au)/$Al_{0.20}Ga_{0.80}N$ SBDs obtained from corresponding reverse bias C-V graphics before and after thermal annealing steps. Each value represents the average of ten diodes.

Annealing temperature (°C)	N_d ($x10^{15}$ cm^{-3})	V_{bi} (V)	Φ_b^{C-V} (eV)	$\Delta\Phi$ (eV)
-	8.606±4.69	0.968±0.056	1.120±0.047	0.0410±0.001
100	5.455±2.84	0.817±0.020	0.971±0.017	0.0390±0.001
200	4.748±3.34	0.890±0.082	1.064±0.064	0.0400±0.001
300	8.857±5.44	1.510±0.037	1.663±0.035	0.0450±0.001
400	10.019±6.11	1.227±0.064	1.377±0.072	0.0430±0.001
500	12.980±7.49	1.439±0.053	1.580±0.047	0.0450±0.001
600	11.081±3.53	1.885±0.019	2.027±0.018	0.0480±0.001

The values of BH obtained from I–V measurements are lower than those obtained from C–V measurements. The difference in the values of BH obtained by I–V and C–V measurements may be attributed to the possible existence of lateral inhomogeneity in the SBH at MS interfaces. As reported by Werner and Güttler (34), the lateral distribution of potentials and barriers differently affect capacitance and dc current measurements. Other possible reason for this difference is the existence of excess capacitance at the interfacial layer due to deep level traps in the semiconductor. The lateral inhomogeneity in the SBH formed at the MS interface is possibly caused by some effects such as inhomogeneities of thickness and composition of the layer, non-uniformity of the interfacial charges, the presence of a thin insulating layer between the metal and semiconductor. Furthermore, there are numerous structural defects, grain boundaries, dislocations, stacking faults at the AlGaN layer, and these may also contribute to SBH inhomogeneity.

4. Conclusion

The effect of thermal annealing on electrical properties of the (Ni/Au)/$Al_{0.20}Ga_{0.80}N$ SBDs were investigated using I–V and C–V measurements. It is shown that the value of SBH increases with increasing annealing temperature. After the annealing at 600°C, the value of the SBH of Ni/Au Schottky contact was found to be 1.755±0.077 eV (from I–V) and 2.027±0.018 eV (from C–V). The obtained results are shown that the optimum annealing temperature for the Ni/Au Schottky contact is 600°C. The variation of SBHs and ideality factors with annealing temperatures may be attributed to the interfacial reactions of Ni/Au with GaN/AlGaN layer. Increment in barrier height by as much as 85.5 % was successfully recorded by thermal annealing at 600°C.

Also, as generally known, chemical reactions between the metal and the semiconductor play an important role in the electrical properties of the metal/semiconductor contact. The change in the barrier height of contact with annealing temperature may also be ascribed to the interfacial reaction occurring between metals and GaN or AlGaN. These interfacial layers may have different work functions than the Ni/AlGaN contact layers which is responsible for the increase of barrier height.

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